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ERROR PATTERNS MEASURED ON TRANSEQUATORIAL HF COMMUNICATION LINKS

MARCH 1967

K. Brayer

Prepared for
AEROSPACE INSTRUMENTATION PROGRAM OFFICE
DEVELOPMENT ENGINEERING DIVISION
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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Project 705B
Prepared by
THE MITRE CORPORATION
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FOREWORD

This report was prepared by the Range Communications Planning and Technology Subdepartment of The MITRE Corporation, Bedford, Massachusetts, under Contract AF 19(628)-5165. The work was directed by the De Development Engineering Division under the Aerospace Instrumentation P Program Office, Air Force Electronics Systems Division, Laurence G. Hanscom Field, Bedford, Massachusetts. Captain J. J. Centofanti served as the Air Force Project Monitor for this program, identifiable as ESD (ESSI) Project 5932, Range Digital Data Transmission Improvement.

REVIEW AND APPROVAL

Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Clement V. Horrigan

for OTIS R. HILL, Colonel, USAF
Director of Aerospace Instrumentation
Program Office

ABSTRACT

As part of The MITRE Corporation's program for improvement of HF communication, the performance of coding and a means for evaluating coding equipment has been presented. * It is, however, preferable to have a channel model upon which various error control techniques can be tried out as opposed to the direct approach, which is available only to the possessor of the data used previously. * This report has been developed with the intention of presenting both the traditional channel modeling statistics (consecutive error distributions and gap-distributions), and a set of new statistics against which modeling can be performed.

The error statistics incurred in the transmission of high frequency digital data at rates of from 600 to 2400 bits per second over various paths of the Eastern Test Range are presented herein. The data was transmitted on and parallel to the range using various modulation systems (modems). It is demonstrated that the errors occur in non-random fashion and in some cases are periodic. These error patterns (especially the periodic ones) present a new, important problem for channel modeling of HF data from a heavily-used transequatorial circuit.

With these statistics, those not having direct access to the data will be able to tackle the problem of modeling this data which doesn't fit any known model (e. g. ,Gilbert, Berkovits, and Pareto).

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* K. Brayer and O. Cardinale, Evaluation of Error Correction Block Encoding for High Speed HF Data, P. G. ComTech, June, 1967.

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SUMMARY

The error statistics incurred in the transmission of high frequency digital data at rates of from 600 to 2400 bit per second over various paths of the Eastern Test Range are presented. The data was transmitted on and parallel to the range using various modulation systems (modems). The statistics of the data are presented as both characterizing statistics and in a form useful for code analysis. It is demonstrated that the errors occur in non-random fashion and in some cases are periodic.

SECTION I

INTRODUCTION

As a part of Cape Kennedy launch operations, information must be transmitted back to the central computers from Ascension Island and Pretoria, South Africa. The present means used for such communication is HF radio. Digital data transmitted over HF radio has an error probability of 10^{-2} during poor channel conditions and 10^{-5} during good conditions, with an average error probability of 5×10^{-3}. This error probability is sufficient for some messages but not for configurations of large sections of real-time data which will become useless. The error rate requires transmission of a large number of samples per second, thus reducing the amount of baseband usable for other purposes. For high reliability in HF data transmission, the error rate must be improved to 1×10^{-5}. Such improvement can be obtained through coding or retransmission if the error patterns are known. The data selected are from the Eastern Test Range path between Antigua Island and Ascension Island and on a path from Pretoria, South Africa, to Riverhead, Long Island, New York. Thus, statistics are available on errors for circuits where a considerable amount of data is relayed and generated.

The use of coding is highly dependent upon the form of error patterns. If errors occur randomly, a random error-correcting code can be used. However, if the errors are not random, the random error-correcting code will not perform well. The data considered herein will be analyzed from the point of view of consecutive errors, intervals between errors, block error rate, and burst occurrence. From these statistics it will be possible to determine whether or not the errors are random and what type of coding is necessary for error correction.

The measuring technique for experimentally obtaining error patterns is simply to transmit a test message, compare the received message with the transmitted message that has been suitably delayed, and record the difference (errors) on magnetic tape. The error data is now permanently recorded and can be used to find statistics such as average error rate, consecutive error occurrence, error-free interval occurrence, and word error rates. This type of statistical probability analysis showed that the errors are not random and, by comparison with theoretical distributions, indicated precisely the deviation from random.

SECTION II

EXPERIMENTAL DATA

The data used was obtained using six different modems. These are the Kineplex TE-202, Kineplex TE-216, AN/FGC-60, AN/FGC-61A and early versions of SC-302 and S-3000. The TE-216 and AN/FGC-60 were used on a looped basis between Antigua and Ascension with both transmission and reception at Antigua and re-routing at Ascension. This test was conducted in October of 1965. The other four modems were used between Pretoria, South Africa, and Riverhead, Long Island, New York, in the spring of 1964. The transmission was on a one-way basis with reception at Riverhead. All transmission used dual diversity with rhombic antennas. An overall description of the data is presented in Table I. Additional information on modem characteristics is available from manufacturers' catalogs.

The error patterns were recorded in the field on magnetic tape and returned to The MITRE Corporation in Bedford, Massachusetts, where they were played through the Tape Converter Facility which generates an IBM-compatible tape. The error data can then be used in the IBM 7030 computer in conjunction with the computer programs which statistically analyze the errors.

The following error statistics were measured on the error data:

a. The cumulative distribution of consecutive errors.

b. The cumulative distribution of consecutive error-free bits.

c. The distribution of errors in n bit blocks where $n = 2^m - 1$ for $m \leq 13$ and $n = 24$. This distribution was used to obtain message error rates.

Table I

Data Description

Modem	Modulation Technique	Data Rate (Bits/Sec)	Total Bits	Average Error Rate
AN/FGC-61A	Frequency shift keying over 16 tones (only 12 tones used)	900	4.6×10^{7}	3.14×10^{-3}
SC-302	Phase-shift keying-frequency differential reference	750	8.4×10^{7}	2.17×10^{-3}
TE-202	Four-phase time differential phase-shift keying	1200	9.8×10^{7}	3.48×10^{-3}
S-3000X	Quadraphase, time/frequency differential coherent phase-shift keying	750	3.8×10^{7}	1.78×10^{-3}
AN/FGC-60	16 tone frequency shift keying	600 1200	2.5×10^{7} 2.6×10^{7}	1.26×10^{-2} 1.10×10^{-2}
TE-216	Four-phase time differential phase-shift keying	1200 2400	8.4×10^{7} 5.2×10^{7}	5.21×10^{-3} 5.16×10^{-3}

The statistics of the eight combinations of modems and transmission rates are presented in Figures 1 to 10, along with the theoretical cumulative distribution functions of random errors for the message error rates and the error-free interval (gap) distribution. The theoretical equations for consecutive errors and gap distribution are:

$$P \left\{ n \text{ consecutive errors} \right\} = P = \left\{ e^{n} c \mid c \right\} = \sum_{k=0}^{n} p^{k} (1 - p) \tag{1}$$

$$P \left\{ n \text{ bit gap} \right\} = P = \left\{ c^{n} e \mid e \right\} = \sum_{k=0}^{n} p(1 - p)^{k} \tag{2}$$

where

P represents cumulative probability

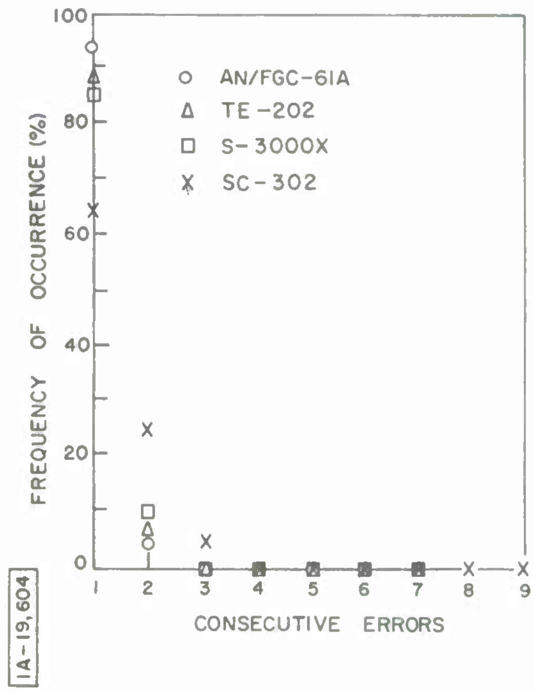
e represents an error bit

c represents a correct bit

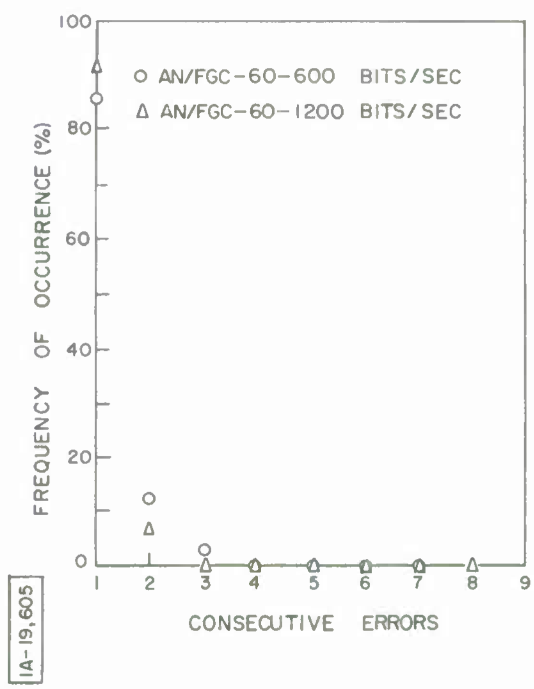
n = number of consecutive bits

p = probability of a bit error

The theoretical relationship indicates, for the occurrence of consecutive errors, that over 98 percent of the error should occur as single errors. In practice, the range is from 65 to 94 percent. Thus (Figure 1a-c), more than the theoretically expected numbers of multiple errors are occurring, which indicates that the errors are tending to cluster. It can also be seen from the distribution of gaps (Figure 2a-c) that there are inordinately high frequencies of short gaps in measured data as opposed to the theoretical distribution (Figure 3). Thus, not only are the errors clustered but the

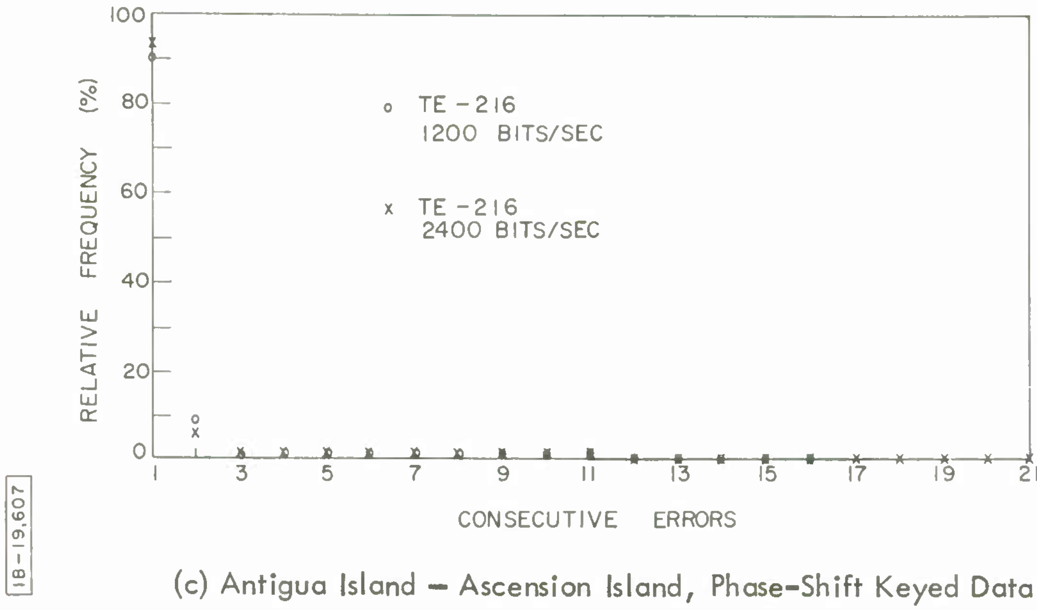


(a) Pretoria, So. Africa — Riverhead, New York, Data



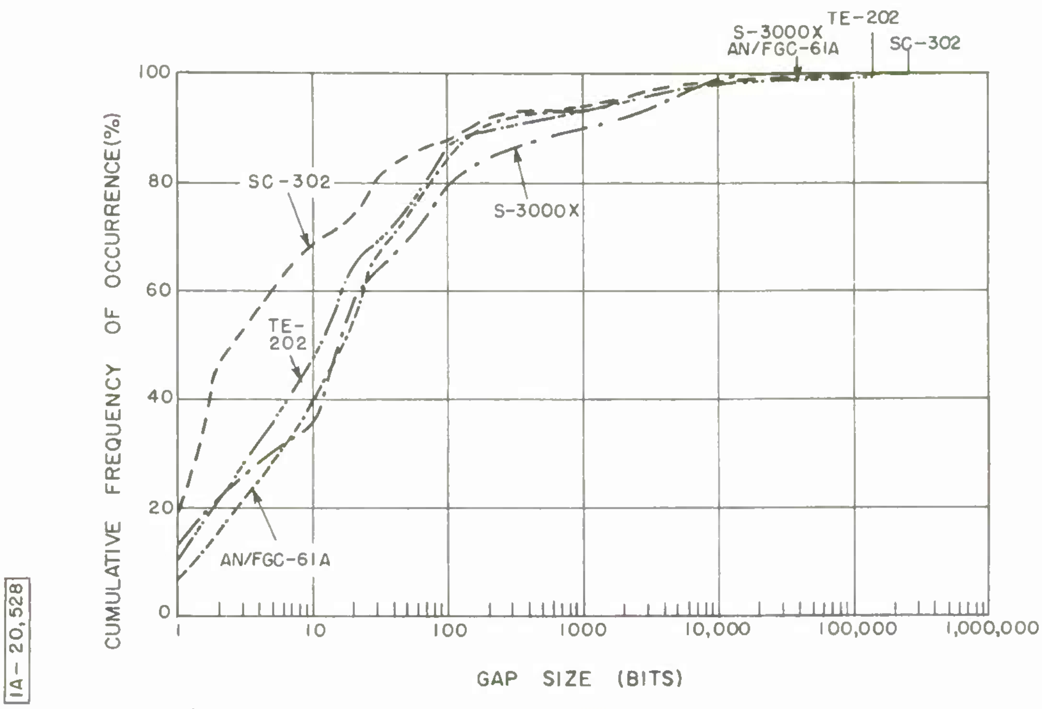
(b) Antigua Island — Ascension Island, Frequency Shift Keyed Data

Figure 1. Frequency of Consecutive Error Occurrence



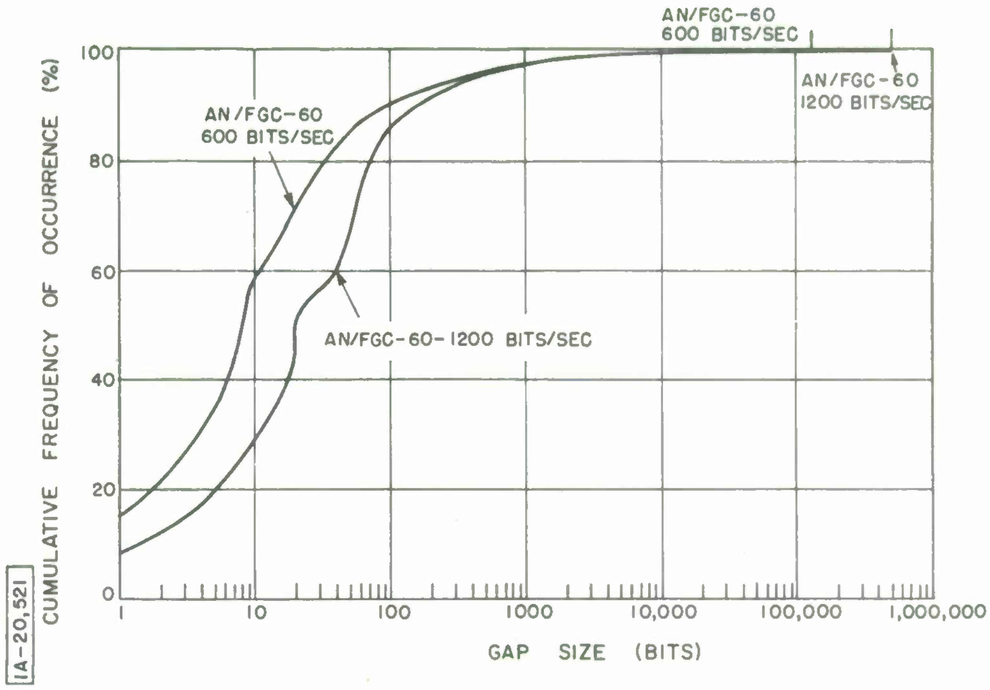
(c) Antigua Island — Ascension Island, Phase-Shift Keyed Data

Figure 1. Frequency of Consecutive Error Occurrence

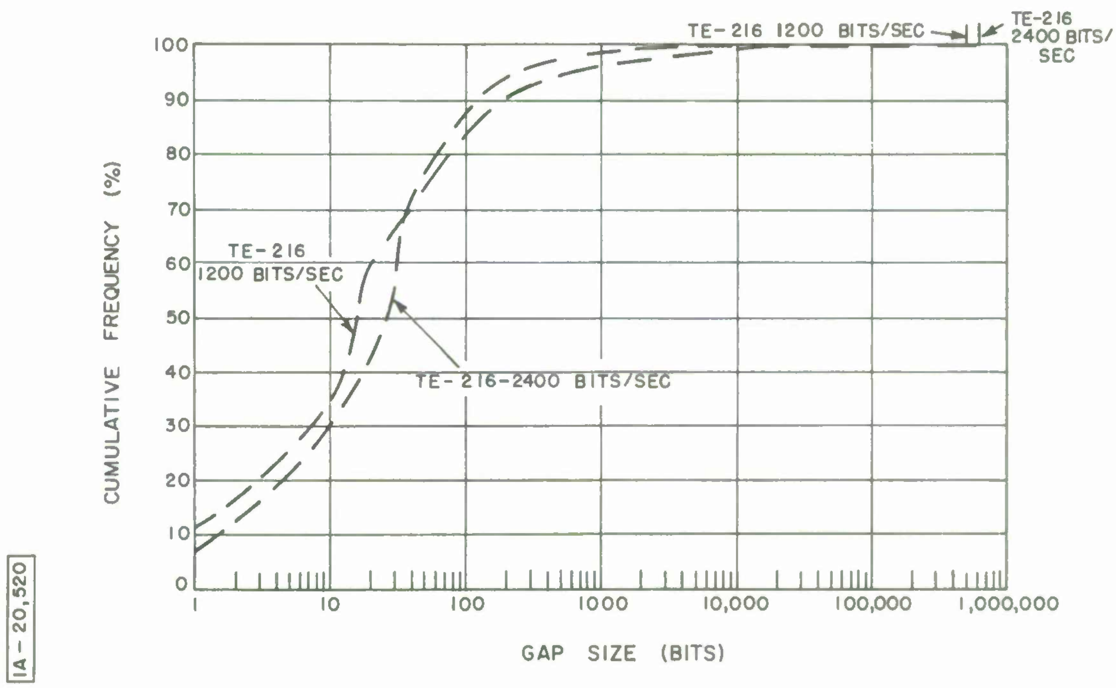


(a) Pretoria, So. Africa — Riverhead, New York, Data

Figure 2. Distribution of Gaps Between Errors



(b) Antigua Island – Ascension Island, Frequency Shift Keyed Data



(c) Antigua Island – Ascension Island, Phase-Shift Keyed Data

Figure 2. Distribution of Gaps Between Errors

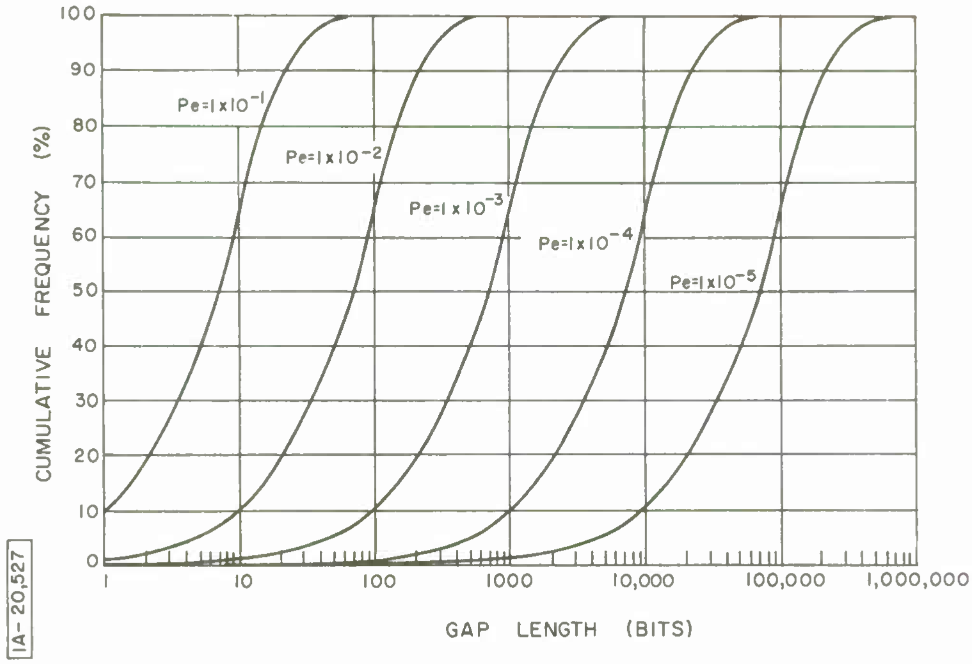


Figure 3. Theoretical Distribution of Gap Lengths

clusters are close together, indicating the occurrence of bursts of errors as opposed to the occurrence of random errors. In the case of the TE-216 modem, there was also an occurrence of periodic errors. This is indicated by the high relative frequencies of gaps (sixteen and thirty-two). It is thought that this is due to the fact that transmission was on parallel tones in a highly congested communications traffic pattern where interference occurred on some tones but not others. After the parallel-to-serial conversion operation which follows detection in the modem, these errors occur periodically. This phenomenon also occurred with the FGC-60 modem for gap sizes of eight and sixteen. The values of periodicity are the modem frame lengths in bits, as would be indicated by the explanation of tone interference.

The theoretical message error rates as a function of message size are derived from the relation, which holds for independent errors (Figure 4),

$$P_m = 1 - \left(1 - P_e\right)^m \tag{3}$$

where

m	=	message length (bits)
P_e	=	probability of bit error
P_m	=	probability of message error

As can be seen from Figure 5(a-b), the probability of a message error is less than would be expected if the errors occurred independently. This is another indication that the errors are occurring in bursts. These message error rates can be used in the design of block retransmission systems since they allow the selection of a message size such that the probability of message error is not excessive. Thus the probability would be high that a message would be received correctly.

It will be demonstrated in the next section that, although the 1200 and 2400 bit per second TE-216 data showed almost the same average bit error rate, more bursts of lengths greater than any finite value are exhibited by the 2400 bit/sec data. This fact indicates that there will be fewer messages in error and the message error rate will more closely approach the bit error rate. As the message length goes to one, every bit becomes a message and the bit error rate equals the message error rate independently of the channel.

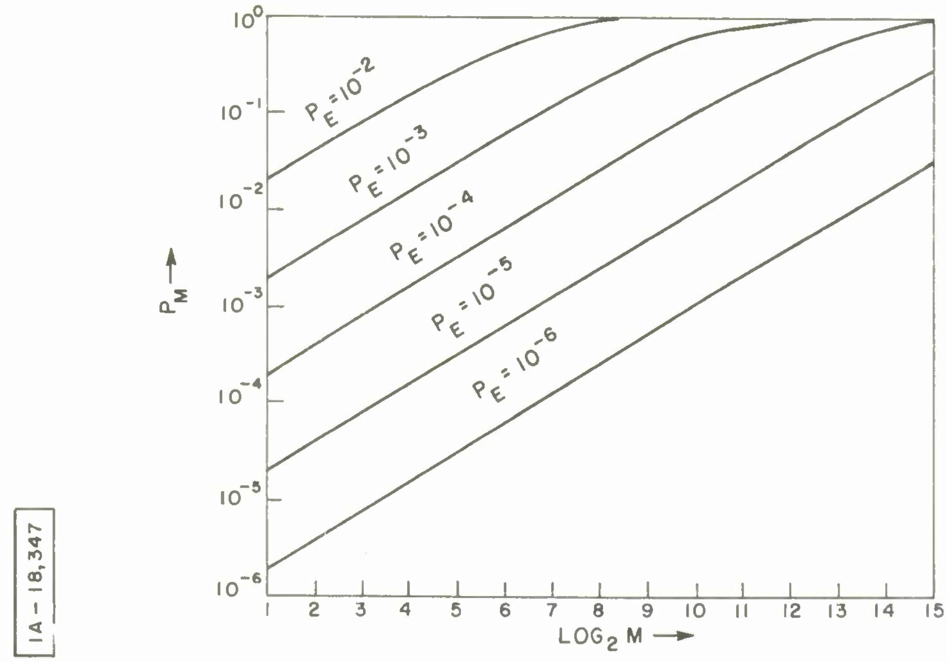
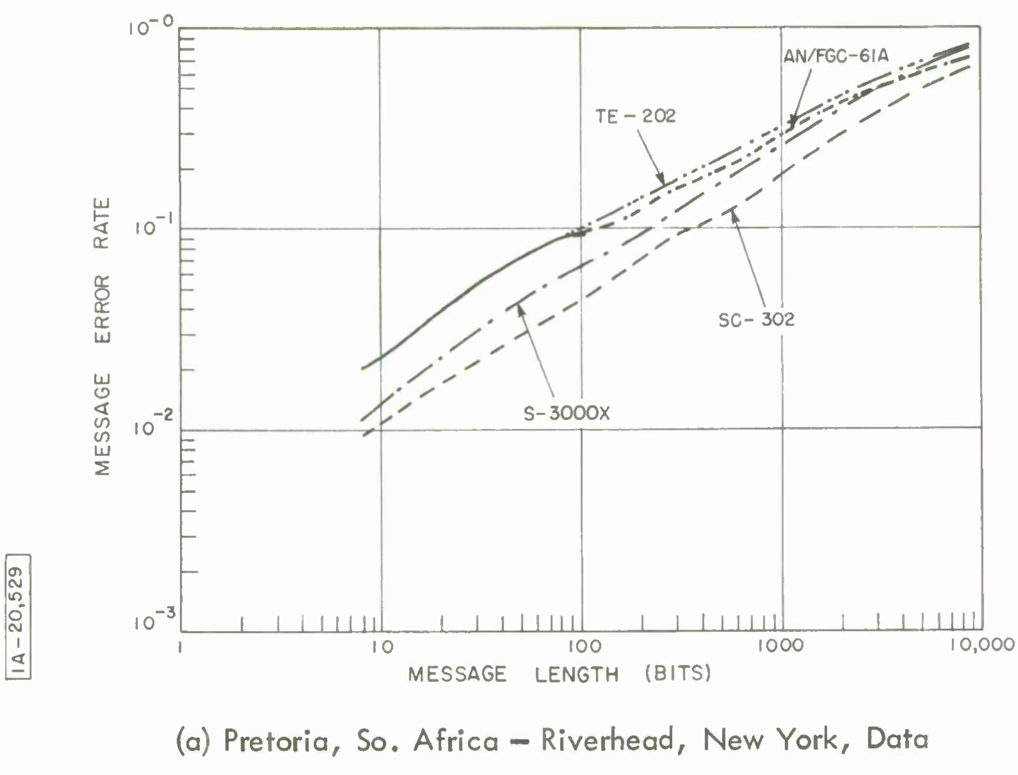
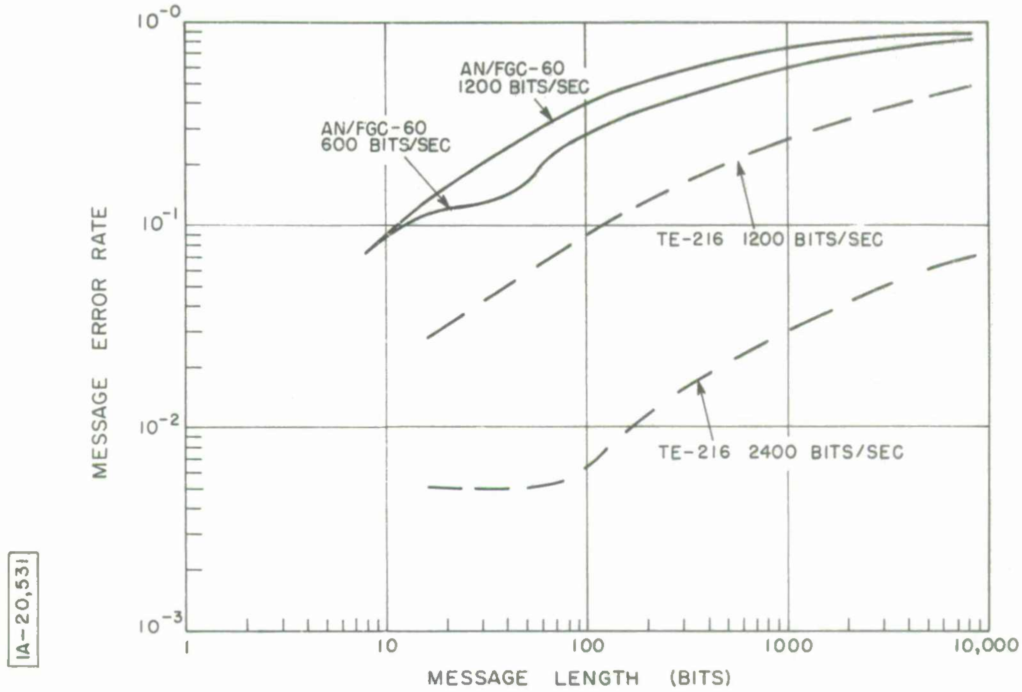


Figure 4. Probability of a Message Error (P_m) as a Function of Bit Error Probability (P_e) and Message Length (M)



(a) Pretoria, So. Africa – Riverhead, New York, Data

Figure 5. Message Error Rate versus Message Length



(b) Antigua Island – Ascension Island, Frequency and Phase-Shift Keyed Data

Figure 5. Message Error Rate versus Message Length

SECTION III

DESCRIPTION OF BURST STATISTICS

The previous discussion of statistics does not present the complete picture. There is no information about the length of bursts, nor is there information relative to the interval between bursts (guard space). For this reason a new burst statistic is defined and presented herein.

Definition of Burst

A burst is defined as a region of the serial data stream where the following properties hold. A minimum number of errors, M_e, are contained in the region and the minimum density of errors in the region is Δ. Both of these conditions must be satisfied for the chosen values of M_e and Δ for the region to be defined as a burst. The density of errors is defined as the ratio of bits in error to the total number of bits in the region.

The following properties hold for the burst. The burst always begins with a bit in error and ends with a bit in error. A burst may contain correct bits. Each burst is immediately preceded and followed by an interval in which the density of errors is less than Δ.

The burst probability density function is defined as the probability of occurrence of a burst of size N where N is any positive integer. The burst size is measured in terms for the total number of bits in the burst. A separate burst probability density function may be determined for each pair of Δ and M_e values.

The minimum number of errors in a burst has been chosen to be two for all the data included here. It was found that larger values of M_e would not change the values of burst length significantly. However, the intervals between the bursts were found to increase drastically so that little meaningful data could be obtained for the burst-to-consecutive interval ratio. When a value of one is selected for M_e, every error becomes a burst and the requirement that a burst begin and end in different errors is violated. Consequently no meaningful data are obtained for this value of M_e.

Definition of Interval

The interval is defined as the region of the serial data stream where the following properties hold. The minimum density of errors is less than Δ, and the region begins and ends in a correct bit. An interval may contain errors. An interval is always immediately preceded and followed by a burst. Thus, each and every bit in the data stream must lie in either a burst region or an interval region.

The interval probability density function is defined as the probability of occurrence of an interval of length L, where L is any positive integer. The interval probability density is a joint function of both Δ and M_e.

The guard space ratio is defined as the ratio of an interval to the burst preceding it.

The burst distribution curves are presented in Figure 6 (a-b). It is evident from these figures that, with the exception of the SC-302 modem, other sets of modems detect the same error patterns in the channel. Since these error patterns were taken with the modem considered as a part of the

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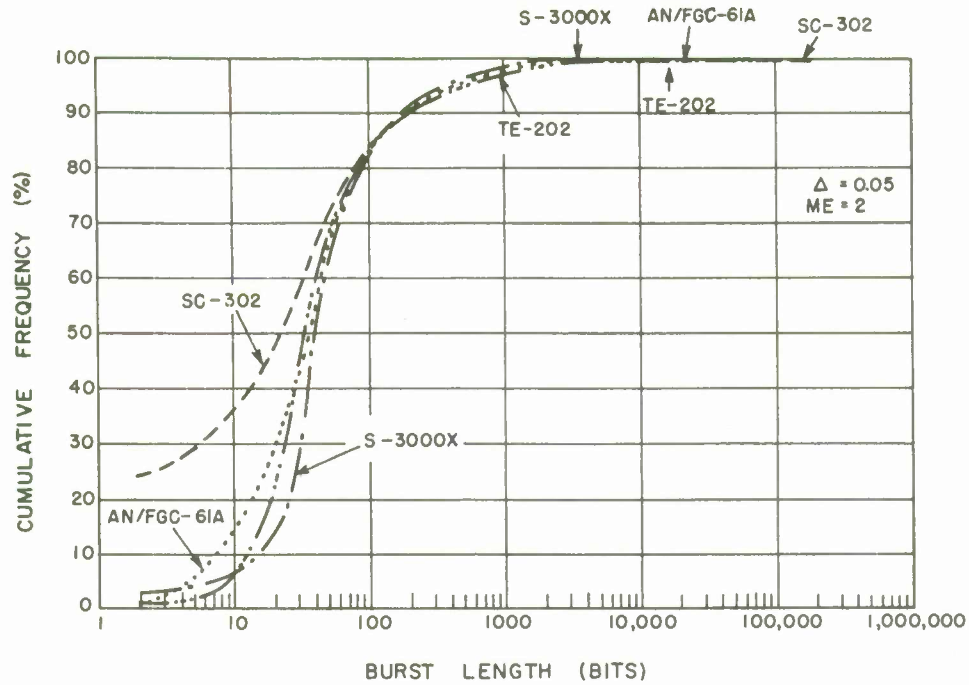

(a) Pretoria, So. Africa – Riverhead, New York, Data

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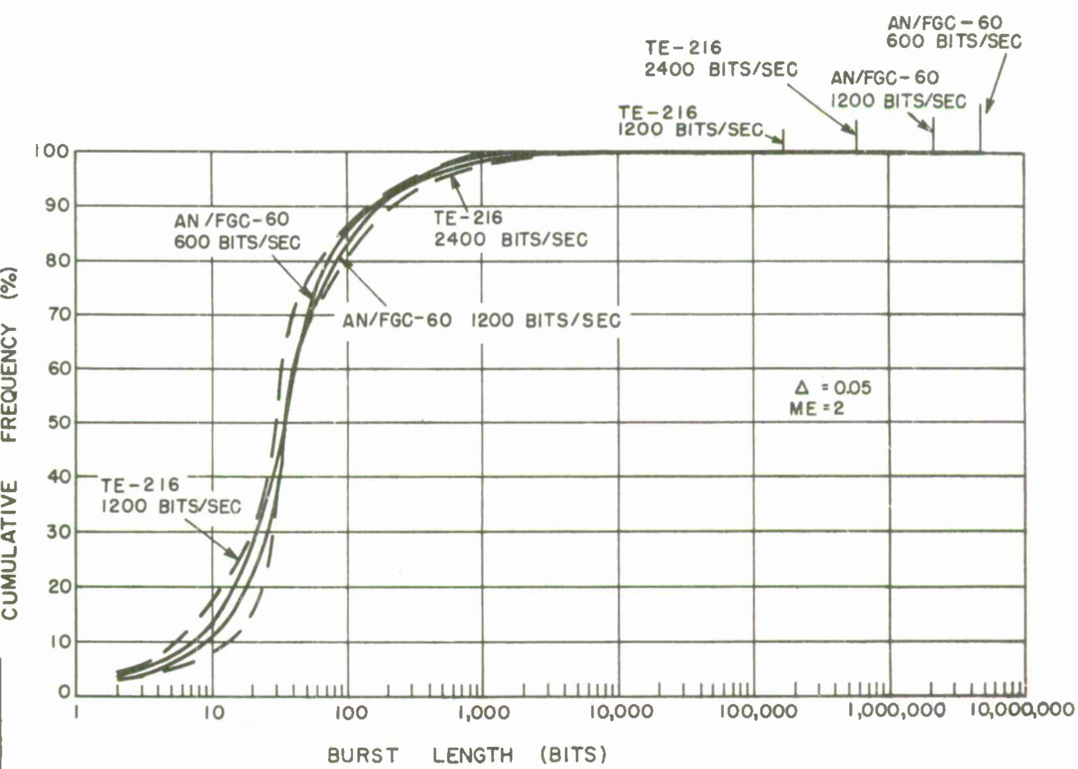


(b) Antigua Island – Ascension Island, Frequency and Phase-Shift Keyed Data

Figure 6. Distribution of Burst Lengths

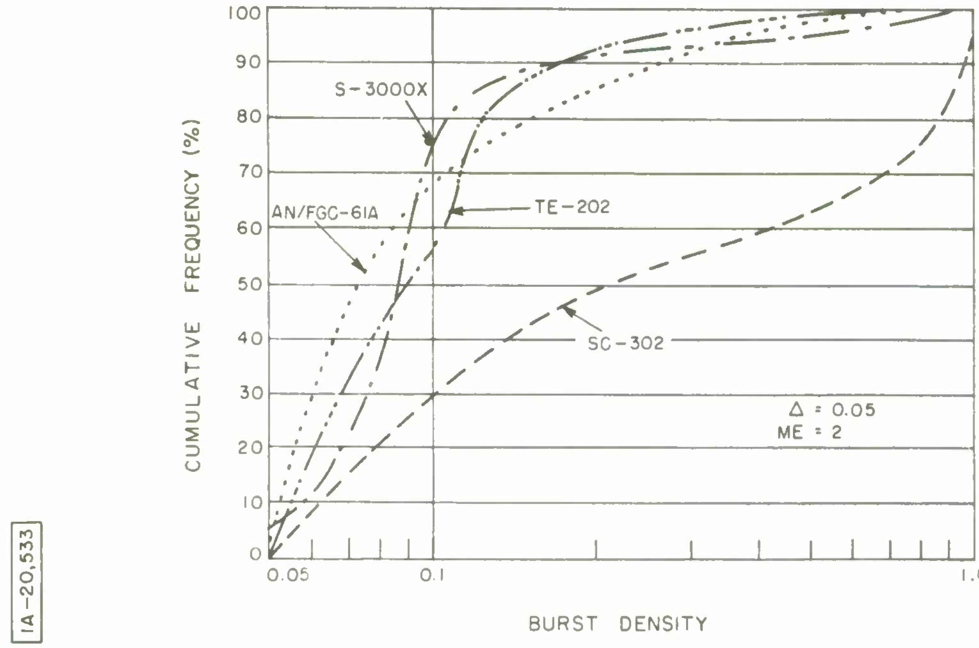
channel, the statement can be made that, with the exception of the SC-302* modem, the other modems performed with the channel in about the same way. These conclusions are further supported by the burst densities of Figure 7 (a-b), the interval lengths in Figure 8 (a-b), the interval error densities of Figure 9 (a-b), and the Burst-Interval Ratios (guard space) distribution of Figure 10 (a-b). From 5 to 22 percent of the bursts are followed by guard spaces less than the burst length and thus cannot be corrected by forward error correcting codes unless interleaving is included. **

The burst density criteria, Δ , was chosen as 0.05 since, for a variation of approximately 0.05, the computer results remain the same and indicate independence of the definition.

---

* Since signal-to-noise ratio, delay distortion, and other error-causing factors could not be easily measured in the channel, there is no way to determine the reason for the different error patterns.

** Brayer, K. and O. Cardinale, Evaluation of Error Correction Block Encoding for High Speed HF Data, to be published in the IEEE Transactions on Communication Technology, June 1967.



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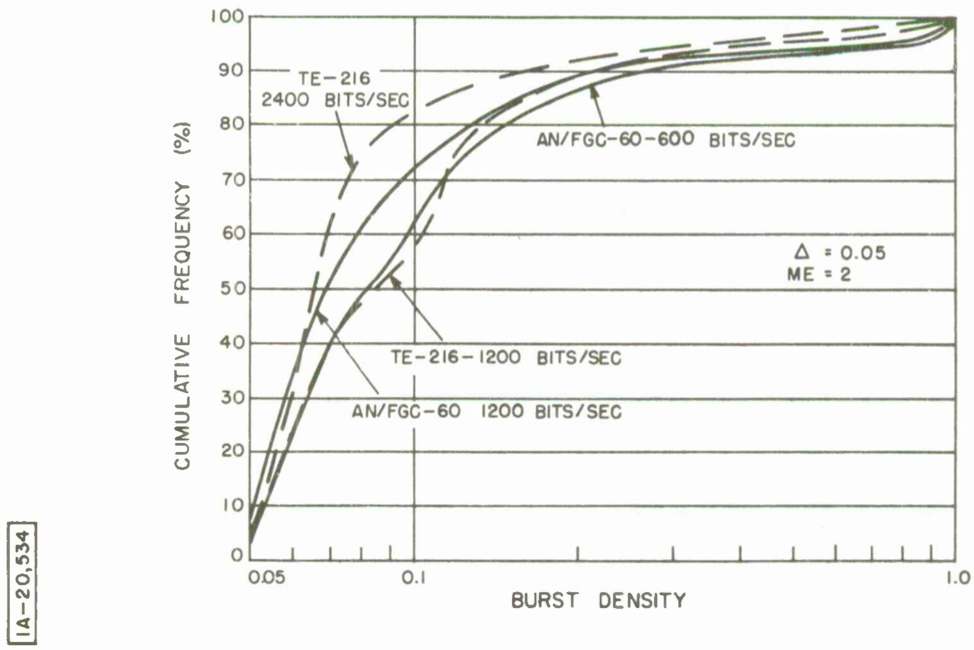
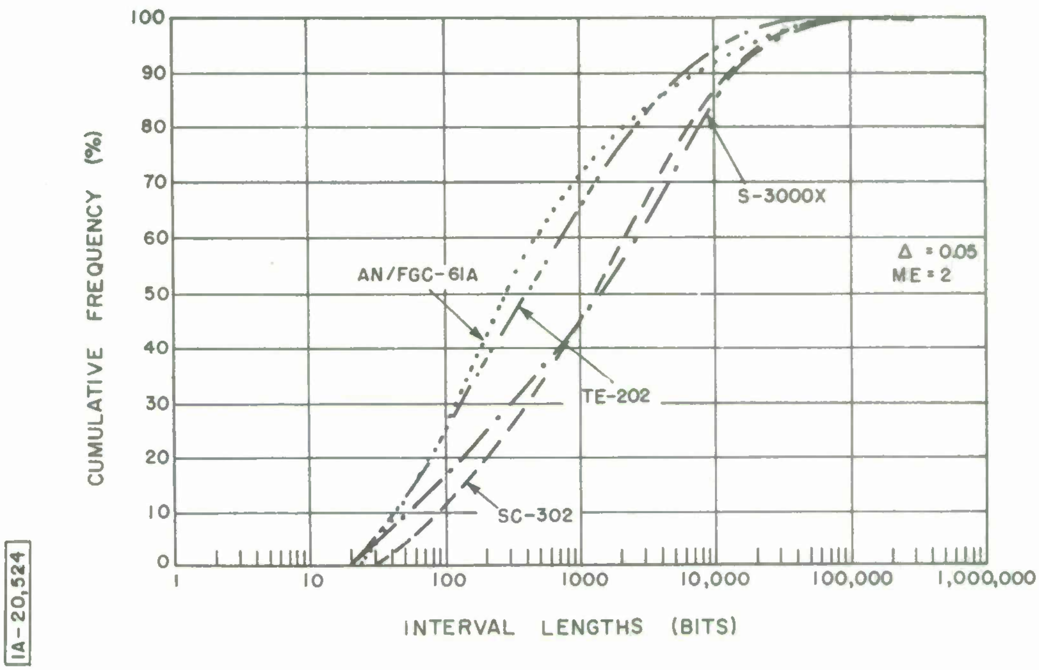


(b) Antigua Island — Ascension Island, Frequency and Phase-Shift Keyed Data

Figure 7. Distribution of Burst Error Density



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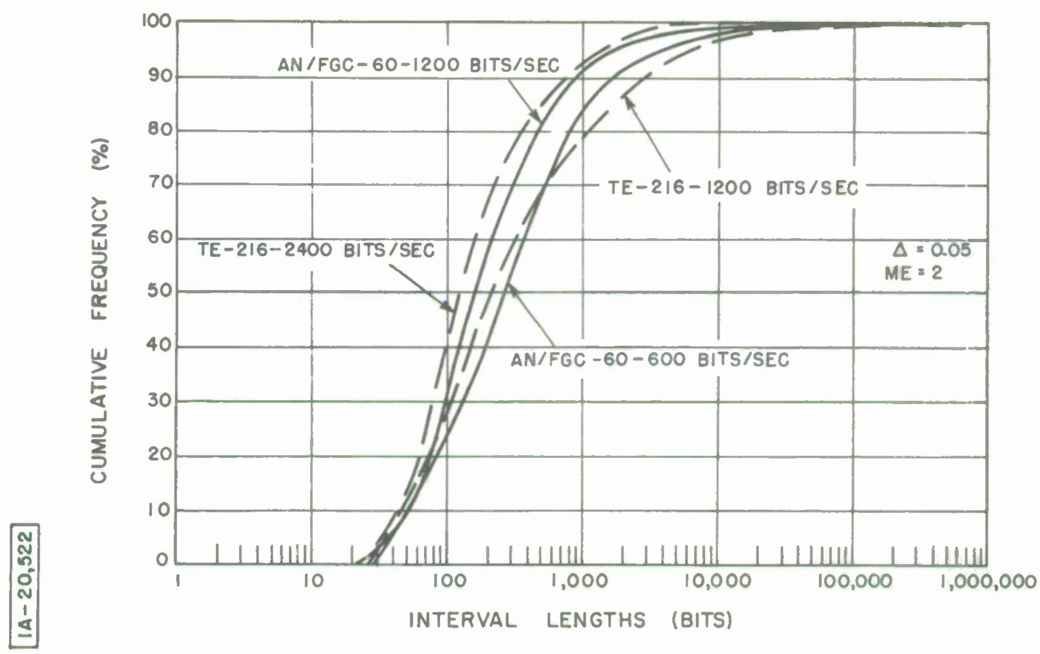
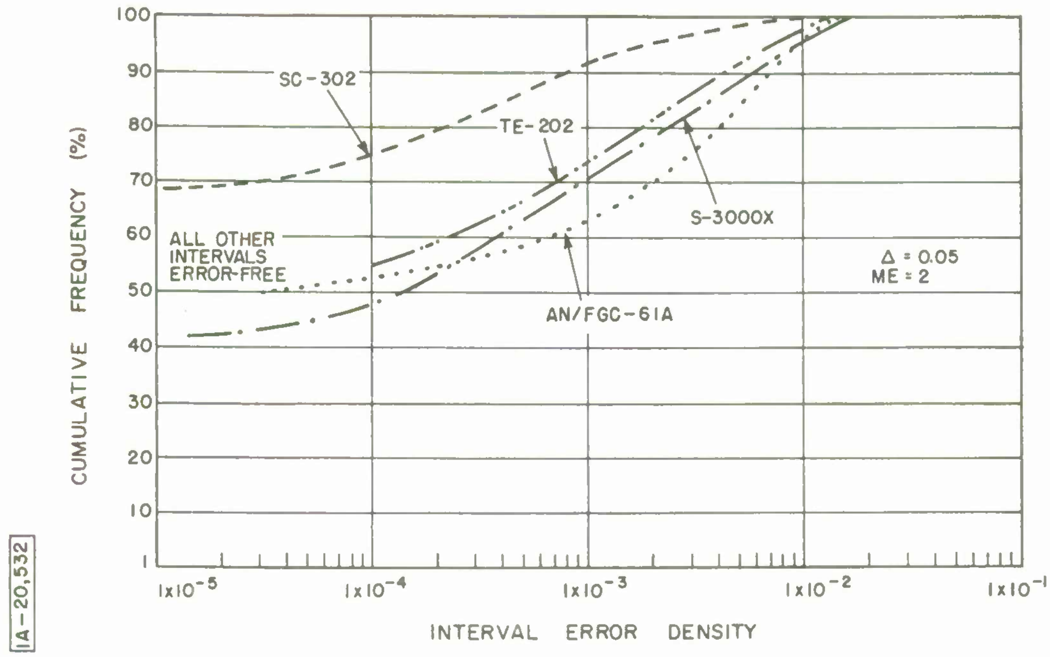
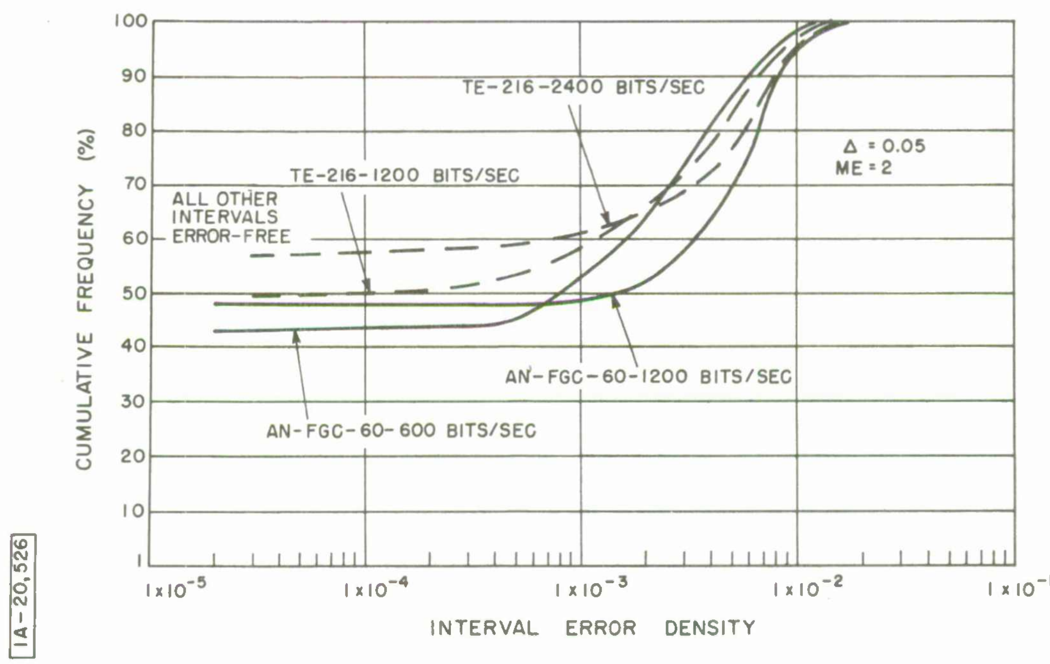


(b) Antigua Island — Ascension Island, Frequency and Phase-Shift Keyed Data

Figure 8. Frequency Distribution on Lengths of Intervals

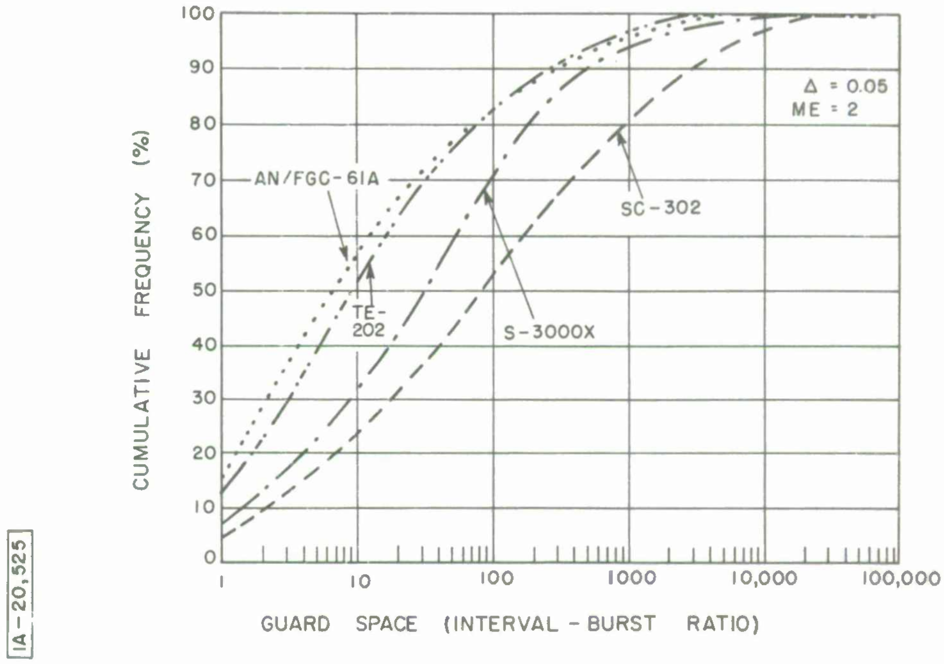


(a) Pretoria, So. Africa — Riverhead, New York, Data

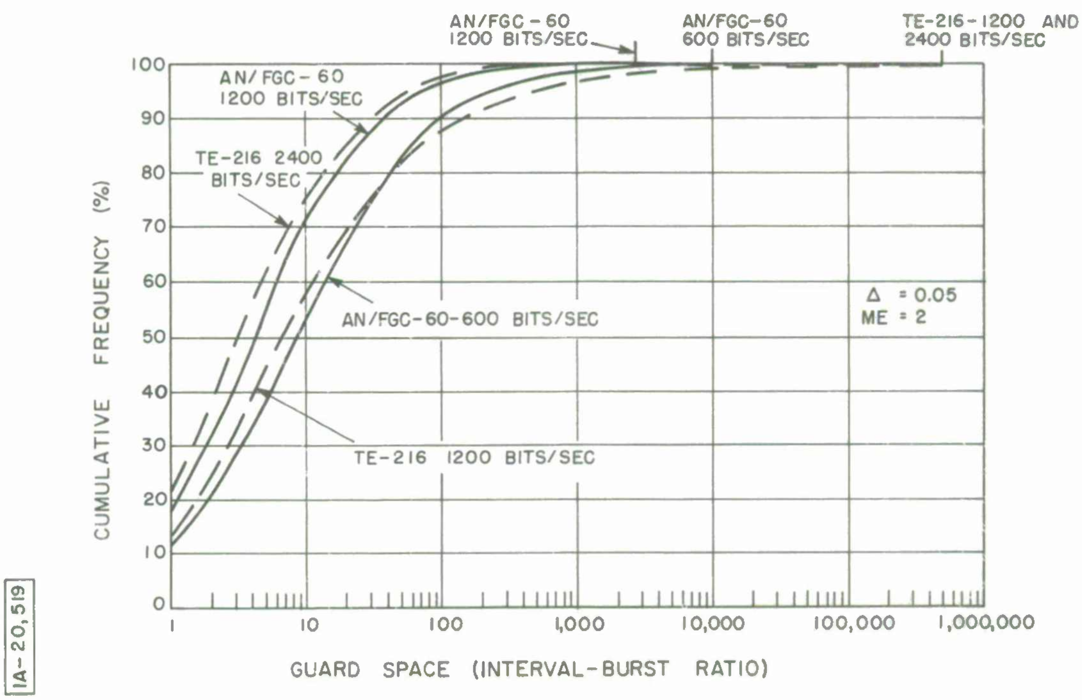


(b) Antigua Island — Ascension Island, Frequency and Phase-Shift Keyed Data

Figure 9. Distribution of Interval Error Density



(a) Pretoria, So. Africa — Riverhead, New York Data



(b) Antigua Island — Ascension Island, Frequency and Phase-Shift Keyed Data

Figure 10. Guard Space Ratio Distribution

SECTION IV

OBSERVATIONS ON THE STATISTICS

While it is the main purpose of this paper to present the statistics of the error patterns on actual HF channels for those design engineers interested in error correction and not to present equipment designs, there are some observations which can be made directly from the data relative to the directions that such designs can take.

Although the errors are certainly not random, the bursts which occur do not fit the traditional definition of bursts of consecutive errors. In all cases the occurrence of long strings of consecutive errors is a rare event. It thus appears that the use of so-called "burst" codes would not be advisable.

The use of block retransmission systems is favored by the statistics since the message error rates for a given block size are less than they would be for random errors.

Further, the data contains information relative to the modem performance. In terms of average error rate, message error rate, or gap distribution, it is seen that there is no degradation in performance with increase in signaling speed. The reason for this is the bursty nature of the data. The data indicates that if a burst of "X" milliseconds occurs, its length is independent of signaling speed and longer bursts do not occur at higher speeds. Furthermore, comparison of the curves for different modems operating in the same channel indicates that the channel error characteristics are relatively independent of the modulation technique.

An example of the way in which a designer would approach the problem of implementing a forward error correction system for the data presented herein can be found in "Evaluation of Error Correction Block Encoding for High Speed HF Data."*

* Op. Cit.

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13. ABSTRACT
As part of The MITRE Corporation's program for improvement of HF communication, the performance of coding and a means for evaluating coding equipment has been presented. * It is, however, preferable to have a channel model upon which various error control techniques can be tried out as opposed to the direct approach, which is available only to the possessor of the data used previously. * This report has been developed with the intention of presenting both the traditional channel modeling statistics (consecutive error distributions and gap-distributions), and a set of new statistics against which modeling can be performed.

The error statistics incurred in the transmission of high frequency digital data at rates of from 600 to 2400 bits per second over various paths of the Eastern Test Range are presented herein. The data was transmitted on and parallel to the range using various modulation systems (modems). It is demonstrated that the errors occur in non-random fashion and in some cases are periodic. These error patterns (especially the periodic ones) present a new, important problem for channel modeling of HF data from a heavily-used transequatorial circuit.

With these statistics, those not having direct access to the data will be able to tackle the problem of modeling this data which doesn't fit any known model (e. g. , Gilbert, Berkovits, and Pareto).

* K. Brayer and O. Cardinale, Evaluation of Error Correction Block Encoding for High Speed HF Data, P. G. ComTech, June, 1967.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
SYSTEMS AND MECHANICS						
Data Transmission Systems						
Multichannel Radio Systems						
Voice Communication (HF) Systems						
INFORMATION THEORY						
Coding						
MATHEMATICS						
Statistical Analysis, HF Error Locations						
Statistical Distribution, HF Error Locations						
Statistical Data, HF Error Locations						

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